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SPECIFIC CONTACT RESISTANCE MEASUREMENTS OF OHMIC CONTACTS TO DIAMOND

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ABSTRACT

We have demonstrated the applicability of the specific contact resistance measurement scheme of Reeves [1] to semiconducting diamond. Four sample types were used: highly doped epitaxial films on <100> and <110> type IIa substrates; a type IIb diamond 0.25 mm thick, and a type IIb diamond 0.05 mm thick. Measured specific contact resistances ranged from $2x10^{-5}$ to $1x10^{-2}$ ohm-cm^2.

INTRODUCTION

The unique material and electronic properties of diamond make it a potentially very important candidate for use in high power or high frequency applications, as well as in high temperature and corrosive environments. Several authors have recently reviewed the motivation and prospects for semiconducting diamond based electronic devices [2-4]. While several critical areas for research were identified, we note that progress has been made in key areas. The growth of large homo-epitaxial films doped with boron, a major step toward the growth of single crystal diamond films on substrates other than diamond, has been reported [5-7]. Regrowth of radiation damage layers created by ion implantation in diamond has also been reported [8]. Success in forming electrical contacts (both rectifying and ohmic) to diamond has also been reported in the literature [9-12]. In this paper measurements of the specific conatact resistance of ohmic contacts to diamond are presented.

Ohmic contacts are characterized by measuring the series resistance arising at the contact-semiconductor junction, R_C. Normalizing the contact resistance to the contact area gives rise to the specific contact resistance, r_C. For the ideal case of uniform current flow perpendicular to the contact we have $r_C=R_C/A$, where A is the contact area. In reality, however, the current flow is rarely perpendicular, and the finite resistance of the semiconductor leads to current crowding [13-15]. Measurement techniques have been developed to allow the current crowding and bulk resistance of the semiconductor to be deconvolved from R_C, thereby uniquely determining the specific contact resistance [15-16]. Conceptually, the simplest technique is that of Cox and Strack [16], in which contacts are made to both the front and back sides of the sample. The primary advantages of this technique are the ease in processing the contacts and the simplified analysis due to the geometry. However, due to the semi-insulating nature of bulk diamond, there is a large series

resistance contribution to the total resistance from the substrate itself. Thus, in order to determine the specific contact resistance one is forced to take the difference of two (nearly equal) large numbers. A second technique utilizes an array of contact pads of equal size, but varying separation contacting a thin conducting layer. The contact resistance in these structures is analyzed using the transmission line model [15]. The primary drawback to transmission line model measurements is the need to perform a mesa etch in order to reduce the analysis of current flow between contacts to a two dimensional problem.

Two techniques for eliminating the mesa etch requirement from the transmission line model measurement have been demonstrated [1,17]. One approach [17] is to simply extend the contact pads across the width of the sample, forming an array of contact lines. The second approach is to use a circular test pattern consisting of a central dot and concentric ring contacts. The measurements are interpreted using a circular transmission line model. For two reasons we judge the second approach to be superior to the first in analyzing diamond samples. First, the use of contact lines requires rectangular (or square) samples and is not adaptable to samples of irregular shape. Second, natural diamonds are frequently non-uniformly doped and the use of circular contacts permits probing over a smaller area. Thus, we chose the circular transmission line model for determining r_C. For the details of the analysis, the reader is referred to reference [1].

Several constraints must be placed on ohmic contacts to diamond. First, they should have a low contact resistance. Second, they should be able to withstand the operating conditions for which diamond devices are intended; e.g. high temperatures. Third, they should be strongly adherent to the diamond surface. Fourth, they should be compatible with conventional device processing techniques. Ohmic contacts produced via a solid state annealing process have been studied extensively and are believed to satisfy all four conditions [9]. In this process a thin film of a transition metal carbide forming metal is deposited on the diamond surface. Annealing at high temperature (950°C) leads to the formation of a carbide layer at the interface. This layer provides an intimate contact to the diamond and promotes good adhesion. Fig. 1 shows the resistance measured between two Molybdenum-diamond contacts as a function of annealing time at 950°C in hydrogen. From the figure it is clear that annealing the contact produced a decrease in total resistance of several orders of magnitude. Auger electron spectroscopy studies indicated that the decrease was associated with the formation of a carbide phase. Similar results have been observed for Ti and Ta contacts. Measurements of the specific contact resistance are required in order to determine the metallizations that provide the lowest electrical impedance for device applications.

EXPERIMENTAL PROCEDURE

Four different diamond samples were used in this study. The first sample consisted of a diamond film with a high boron concentration and about 4 μm in thickness grown epitaxially on a <100> type IIa insulating diamond substrate with the dimensions of 5 x 5 x 0.25 mm. The second sample consisted of a 6 μm thick diamond film with a high boron concentration grown epitaxially on a <110> substrate. These films were grown at MIT Lincoln Labs

using the procedure outlined in [6] on natural diamond substrates provided by Druker International, B.V. The third sample was an irregularly shaped type IIb diamond 0.25 mm thick. The fourth sample was identical to the third, except that it had been thinned to 50 μm in thickness.

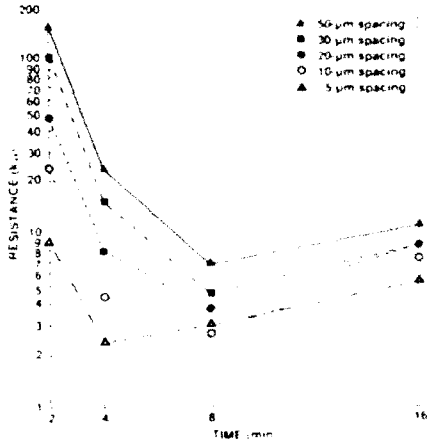

Figure 1 Resistance between two Mo/diamond contacts as a function of annealing time at 950°C in an H_2 ambient.

The samples were cleaned using decontam, deionized water, and ethanol, sequentially. The samples were then coated with photoresist and patterned using standard photolithographic techniques. Samples were baked at 120°C for 20 minutes following photoresist patterning and loaded into an ion pumped ultra-high vacuum system (base pressure 5 x 10^{-9} Torr). Electron beam evaporation was used for deposition of the carbide forming metal (either Ti or Mo). The thickness of the carbide forming metal was about 100 Å. Subsequently, 1500 Å of Au was deposited from a resistively heated boat onto the surface of the Ti or Mo without breaking vacuum to prevent oxidation prior to annealing. The pressure during evaporation was 2 x 10^{-7} Torr. Film thicknesses were determined using a crystal monitor during deposition. After deposition a lift-off process was used to remove undesired metal, leaving contact structures with the geometry shown in Fig. 2. The dimensions (in the notation of Reeves) were $r_1'=1.65r_0$, $r_1=2.74r_0$, $r_2'=4.34r_0$, and $r_2=5.45r_0$ with r_0 =11.7 μm.

Following patterning, the contact structures were probed using a Keithley model 220 current source and model 196 DMM. After probing, the samples were baked at 120°C for approximately 20 minutes and then annealed in a purified hydrogen ambient at 950°C. Anneal times were 2 minutes for Ti and 6 minutes for Mo. After annealing, the samples were remeasured.

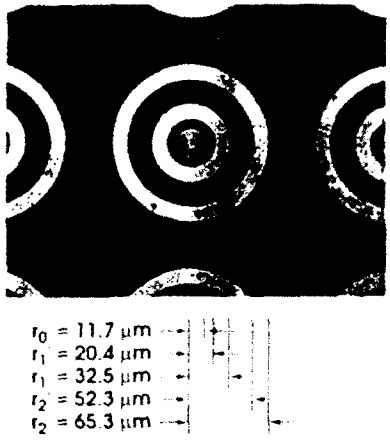

Figure 2 Circular contact pattern used for this work. The dimensions are $r_1'=1.65r_0$, $r_1=2.74r_0$, $r_2'=4.34r_0$, and $r_2=5.45r_0$ with r_0 =11.7 μm.

The measurements consisted of placing tungsten probes on the inner dot, the central ring and the outer ring. The total resistance between the central ring and the inner dot, and the central ring and the outer ring were measured. The end resistance was determined by passing a current through the central ring and the inner dot and measuring the voltage between the central ring and the outer contact. This result was checked by switching contact pairs and remeasuring. Using these three results, the specific contact resistance can be calculated in the manner of [1].

RESULTS AND DISCUSSION

Ohmic contacts between a metal and a semiconductor may be formed either by lowering the effective barrier height, or by heavily doping the semiconductor at the interface. Heavily doping the semiconductor induces a decrease in barrier thickness, allowing tunneling of the charge carriers. Lowering the barrier height is difficult since diamond has a barrier height essentially independent of the metal work function [18]. Increasing the doping in natural semiconducting diamond is a non-trivial task, but may be accomplished rather easily during epitaxial growth of diamond. Table I shows the values of specific contact resistance determined in this experiment. It is interesting to note that contacts to the epitaxial layers (epi-<100> and epi-<110>) showed excellent behavior as deposited. Contacts formed by placing tungsten probe tips on the diamond surface showed only a slight deviation from linearity. Contacts formed by the Ti films were highly linear. This may be due to the highly doped nature of these layers. The measured value of specific contact resistances after annealing are more than satisfactory for device fabrication. Lightly doped diamond (represented by the "thin"

and "thick" samples) are much more difficult to contact. Non-ohmic behavior was observed for the as-deposited contacts in these samples.

Several factors influence the accuracy of these measurements. Of primary importance is the thickness of the conducting layer. Correct interpretation of the transmission line measurements requires that current flow between contact pads be two dimensional, i.e., no vertical flow of current in the diamond. For the epitaxial layers this condition may be assumed to be approximately true. For the 50 μm and 250 μm (bulk) layers, however, there is almost certainly a large component of vertical current flow in the sample. This adds a large spreading resistance term to the overall contact resistance, which in turn greatly adds to the complexity of the transmission line analysis. The possibility of using an approximate geometric correction factor for the thickness of the diamond is being explored.

Table I
Specific Contact Resistance Results for Various Samples

Sample	Conducting Layer thickness (μm)	Metal	N_A (cm^{-3}) at 300 K	r_C (Ω-cm^2) As-deposited	r_C (Ω-cm^2) Post Anneal
epi-<100>	4	Ti	$2x10^{19}$	$3.2x10^{-6}$	$1.8x10^{-5}$
epi-<110>	6	Ti	$7x10^{19}$	$7.6x10^{-5}$	$2x10^{-5}$
thin	50	Mo	(a) 10^{14}	over-ranged	$1.2x10^{-3}$
thick	250	Mo	(a) 10^{14}	over-ranged	$1.4x10^{-2}$

(a) Representative value from other type IIb diamond samples.

It is also of interest to note the specific contact resistance of the SiC and Ta carbide contacts on type IIb natural diamond substrates studied by Fang, et al [11]. They obtained an average value of about 1×10^{-3} ohm-cm^2 for both cases. The conventional linear transmission line was used in their study leading to the necessity of forming a mesa. This was accomplished using a CF_4 plasma etch. A thin conducting layer was formed by inducing ion damage in the diamond. Thus the difference in r_C between the two studies may be due a difference in doping level, a difference in contacting lightly damaged diamond versus undamaged diamond, or an effect of the plasma etch.

CONCLUSIONS

Specific contact resistance for the Ti and Mo refractory metal carbide contacts to diamond have been measured. The values determined from the contacts to the bulk type IIb diamond samples are in reasonable agreement with those published previously [11] for SiC or Ta carbide contacts, indicating the usefulness of the circular transmission line model in avoiding a mesa etch and allowing specific contact resistances to be easily determined.

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